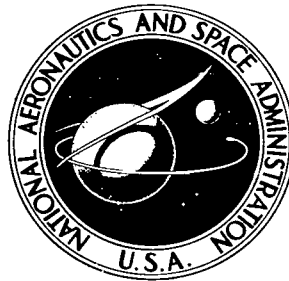


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FRICITION TORQUE OF BALL BEARINGS  
WITH BURNISHED  $\text{MoS}_2$  FILMS  
AT  $10^{-10}$  TORR AT SEVERAL LOADS  
USING FIVE RETAINER MATERIALS

*by David E. Brewe, Herbert W. Scibbe,  
and William J. Anderson*

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16. Abstract <p>Bearing torque was determined for burnished molybdenum disulfide 20-mm-bore ball bearings operating at a shaft speed of 3600 rpm, with thrust loads from 35 to 100 lbf (156 to 445 N), and at pressures of 10<sup>-10</sup> torr (1.3×10<sup>-8</sup> N/m<sup>2</sup>). Among the retainer substrate materials of cast bronze, porous bronze, AISI 440 C stainless steel, AMS 4892 nickel base alloy, and copper, bearings using cast bronze retainers were consistently lower in bearing torque. Use of copper retainers resulted in erratic bearing torque. The magnitude of bearing torque was comparable to that of conventional oil-lubricated bearings. Torque increased linearly with increasing thrust load. Continued running of the bearing as long as 20 hours resulted in slightly higher values of bearing torque.</p>				13. Type of Report and Period Covered <b>Technical Note</b>	
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# FRICION TORQUE OF BALL BEARINGS WITH BURNISHED $\text{MoS}_2$ FILMS AT $10^{-10}$ TORR AT SEVERAL LOADS USING FIVE RETAINER MATERIALS

by David E. Brewe, Herbert W. Scibbe,  
and William J. Anderson

Lewis Research Center

## SUMMARY

Twenty-millimeter-bore ball bearings with metallic retainers were burnished with molybdenum disulfide ( $\text{MoS}_2$ ) and run at pressures of  $10^{-10}$  torr ( $1.3 \times 10^{-8}$  N/m<sup>2</sup>). The burnished surfaces were the race grooves, the inner-race land, the ball set, and the retainer rubbing surfaces. Retainers were fabricated of five different alloys which served as the substrate materials for the  $\text{MoS}_2$  coating. The five alloys were cast bronze, porous bronze, oxygen-free high-conductivity (OFHC) copper, AISI 440 C stainless steel, and AMS 4892 nickel-base alloy. This lubricating technique and the retainer materials were evaluated by measurement of bearing friction torque in the vacuum environment. The bearings were operated at 3600 rpm, at thrust loads from 35 to 100 pounds (156 to 445 N), and for run times as long as 20 hours.

The measured friction torque was 0.6 to 1.8 inch-ounce (0.4 to 1.3 cm-N) for the range of conditions and test times in this investigation. For a 20-millimeter-bore ball bearing running with a bearing torque of 1 inch-ounce (0.7 cm-N) at a 100 pound (445 N) thrust load, the overall friction coefficient is 0.0016. This compares with a typical friction coefficient for a conventional oil lubricated bearing of 0.0013. From this low friction torque, it was concluded that burnishing with  $\text{MoS}_2$  is a desirable means to lubricate bearings for ultrahigh-vacuum service.

Bearings using cast bronze retainers were consistently lower in bearing torque than those bearings using the other four retainer materials.

Bearing torque increased linearly as thrust load was increased. This effect of bearing torque with thrust load was generally repeatable. Bearing torque increased slightly with continued run time for a given load condition. Notable exceptions to this were bearings using OFHC copper as the substrate retainer material. These bearings had the highest and most erratic bearing torque. In addition bearing torque increased very rapidly with run time.

Films of  $\text{MoS}_2$  were formed in the rolling contact and sliding areas. These films typically had a glazed appearance. Blisters of  $\text{MoS}_2$  were formed in the land areas of some of the bearings. The formation of blisters is potentially detrimental to smooth bearing performance.

## INTRODUCTION

Lubrication problems result when rolling-element bearings, which are used in spacecraft and satellite mechanical systems, are exposed to ultrahigh vacuum ( $10^{-10}$  torr or  $1.3 \times 10^{-8}$  N/m<sup>2</sup>) in outer space. Several methods using either liquid or grease lubrication have been tried with varying degrees of success. These were (1) applying silicone oil or grease directly to the bearing (ref. 1), (2) evaporation of an oil through the bearing from an impregnated reservoir as was done in the Tiros II satellite, and (3) impregnation of bearing retainers with different liquid lubricants (ref. 2). Rapid evaporation of the liquid or grease lubricants in the low-pressure environment, however, severely limits the useful life of bearings for ultrahigh vacuum applications. Further satellites requiring optical mechanisms in the vicinity of the bearing cannot risk the liquid lubricant condensing on the optical surfaces.

Reasonable success has been achieved with bearings using self-lubricating retainers, such as filled plastics and filled metals, in ultrahigh vacuum (refs. 3 and 4). Torque was measured using bearings with filled Teflon retainers in reference 3. In comparison with the retainer oil impregnation experiments of reference 2, the measured torque was for the most part lower, but it was at times more erratic. In reference 4, the friction and wear of bearings using retainers made from metal-solid lubricant composites or plastic filled materials were compared. A bearing with a silver-polytetrafluoroethylene-tungsten diselenide (Ag-PTFE-WSe<sub>2</sub>) retainer had the least wear and lowest friction of all the material combinations tested for run times up to 100 hours.

Haltner (ref. 5) conducted sliding friction test in ultrahigh vacuum using coatings of lamellar solid lubricants such as molybdenum disulfide (MoS<sub>2</sub>), tungsten diselenide (WSe<sub>2</sub>), and niobium diselenide (NbSe<sub>2</sub>) between the sliding surfaces. These studies indicated that WSe<sub>2</sub> and NbSe<sub>2</sub> did not perform as well in ultrahigh vacuum as did natural molybdenite (MoS<sub>2</sub>).

Solid lubricant films, such as burnished MoS<sub>2</sub>, can be applied to all bearing surfaces. These films are extremely thin, on the order of 10 microinches (0.25  $\mu$ m), and can provide good lubrication in the vacuum environment (ref. 6). Johnson, Buckley, and Swikert (ref. 7) showed that a burnished MoS<sub>2</sub> film applied in an inert-gas atmosphere had good endurance characteristics and that it was at least as good as the more complex bonded films (e.g., phenolic epoxy and sodium silicate bonded films). The investigators of reference 8 operated 25-millimeter-bore ball bearings with burnished MoS<sub>2</sub> films in  $10^{-7}$  torr ( $1.3 \times 10^{-5}$  N/m<sup>2</sup>) vacuum. The bearings were operated continuously for approximately 800 hours at low speed with a 10-pound (44-N) radial load. The measured torque values were less than 1.6 inch-ounces (1.1 cm-N) for the entire running period.

The objectives of this investigation were (1) to evaluate burnished MoS<sub>2</sub> films as a bearing lubricating technique in ultra-high vacuum by measuring bearing friction torque,

(2) to determine the effect of retainer substrate material on bearing torque with this lubrication scheme, and (3) to determine the effect of run time on bearing friction torque for several loads.

The burnished  $\text{MoS}_2$  film lubricating technique was evaluated with 20-millimeter-bore, size 204 ball bearings. The burnished  $\text{MoS}_2$  film was applied to both inner and outer race grooves, the inner race land, the balls, and the rubbing surfaces of the retainer. Five retainer materials were used: (1) cast bronze, (2) porous bronze, (3) AMS 4892 nickel-base alloy (S-monel), (4) AISI 440 C stainless steel, and (5), oxygen-free high-conductivity (OFHC) copper. All tests were conducted at ambient pressures of approximately  $10^{-10}$  torr ( $1.3 \times 10^{-8}$  N/m<sup>2</sup>), thrust loads of 35 to 100 pounds (156 to 445 N), and at a speed of 3600 rpm. Bearing total run times varied from 1 to 20 hours.

## APPARATUS

### Bearing Test System

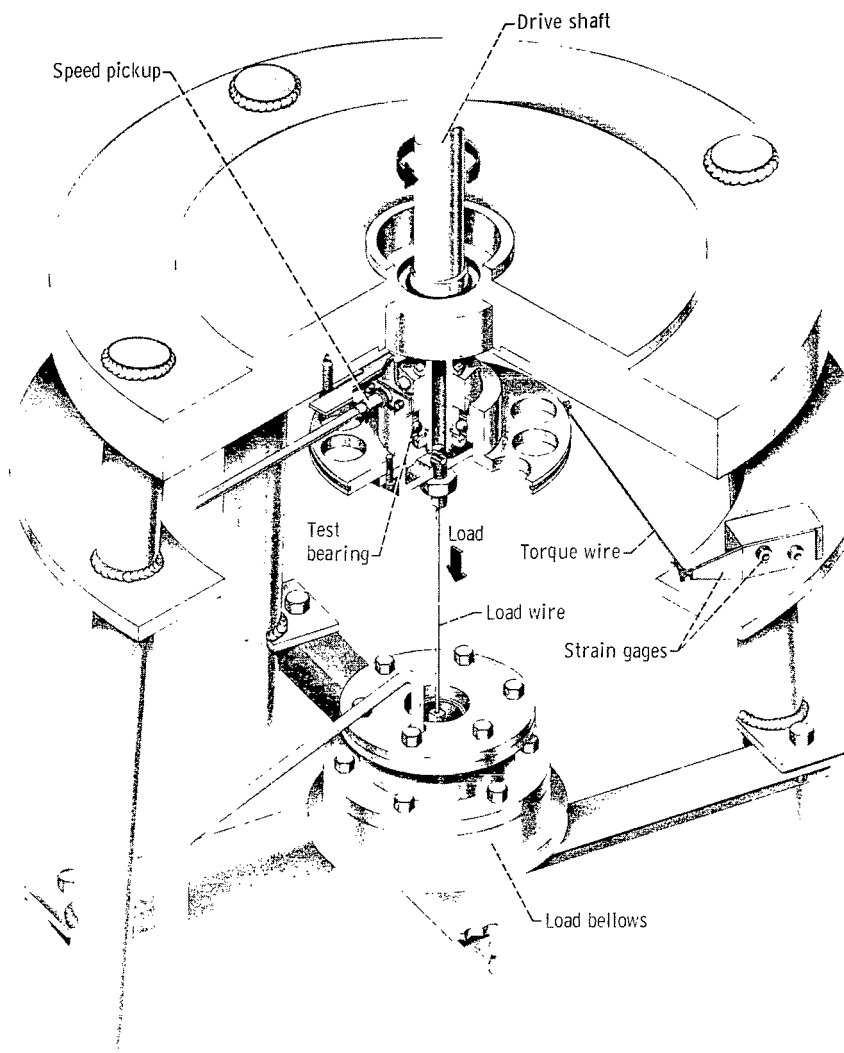
A cutaway view and a cross section of the test-bearing arrangement are shown in figure 1. The test bearing was operated in vacuum and loaded axially by pressurizing the load bellows with compressed air. A stainless-steel wire, connecting the load bellows and the bearing housing, transferred the load. The load bellows was calibrated with a strain-gage ring. The load capacity of the system was approximately 150 pounds (667 N).

The test-bearing shaft was driven by a 1/4-horsepower (186 W) canned induction motor located inside the vacuum chamber. The test shaft rotated at a nominally constant speed of 3600 rpm. A magnetic speed pickup was used to monitor the shaft speed.

The test shaft was mounted vertically and supported by the drive-motor bearing. The drive-motor bearings were water cooled and the stator was oil cooled to prevent overheating.

A thermocouple welded in the bearing housing and pressed against the outer race of test bearing was used to measure the bearing temperature (fig. 1(b)). The thermocouple output was continuously recorded on a strip-chart recorder.

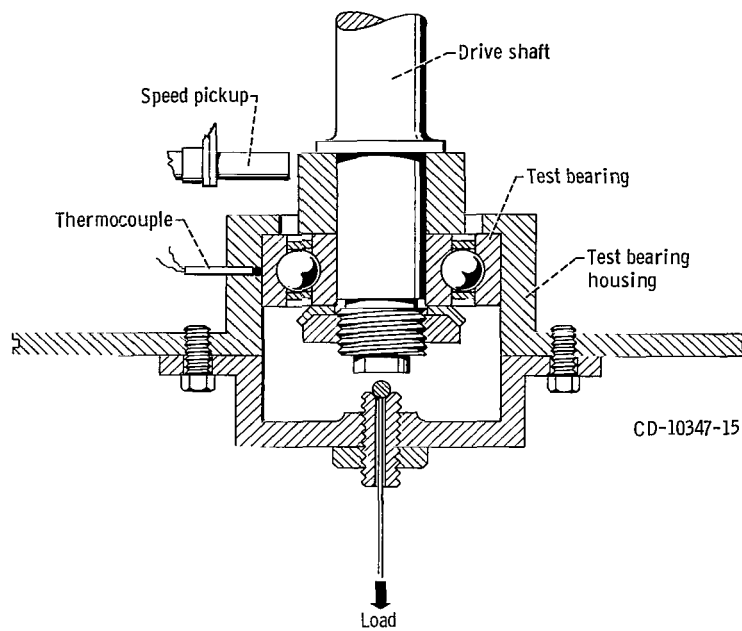
A force transducer, which was connected to the bearing housing, measured the test-bearing torque (see fig. 1(a)). The transducer consisted of two ceramic-bonded strain gages mounted on each side of an accurately machined, 0.015-inch (0.038-cm) thick cantilever beam. The two strain gages were connected to a four-arm bridge circuit such that beam deflection resulted in a voltage output. The voltage, representing test bearing torque, was recorded continuously with a millivolt potentiometer.



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(a) Cutaway view.

Figure 1. - Bearing test assembly.



(b) Detailed view of test-bearing mounting.

Figure 1. - Concluded.

## Vacuum System

The test apparatus is mounted in an 18-inch (46-cm) diameter by 62-inch (157-cm) long steel vacuum chamber. The pumping system consists of a roughing pump, an ionization pump, a titanium sublimation pump, a cryopanel, and resistance bakeout heaters. The roughing pump is a series of six sorption pumps that are capable of evacuating the chamber from atmospheric pressure to a pressure of  $10^{-3}$  torr ( $0.13 \text{ N/m}^2$ ) in about 25 minutes. The ionization pump has a pumping speed of 0.500 cubic meters per second and is capable of evacuating the chamber to an ultimate pressure of  $10^{-10}$  torr ( $1.3 \times 10^{-8} \text{ N/m}^2$ ) when used with the resistance bakeout heaters. The resistance heaters are attached to the outside of the vacuum chamber and to the inside of the ionization pump and are used to bake out gases adsorbed on the inner surfaces of the chamber. The bakeout operates for periods up to 24 hours and regulates chamber temperature to a maximum value of  $480^\circ \text{ F}$  ( $522 \text{ K}$ ). A pressure sensitive relay is used during the bakeout cycle to shut off the ionization pump to prevent damage during periods of excessive gas loads. The cryopanel filled with liquid nitrogen at  $-320^\circ \text{ F}$  ( $78 \text{ K}$ ), and the titanium sublimation pump are used, after the bakeout cycle, to assist the ionization pump in obtaining an ultimate chamber pressure of  $10^{-11}$  torr ( $1.3 \times 10^{-9} \text{ N/m}^2$ ).

Pressure measurements in the chamber were made with a hot-cathode, nude ionization gage mounted approximately 24 inches (61 cm) below the test bearing housing and 12 inches (30 cm) above the ion pump throat.

# MATERIALS

## Test Bearings

All runs were made with size 204 (20-mm bore) ball bearings (see fig. 2) made from AISI 440 C stainless steel. One shoulder on the outer race was relieved to make the bearings separable. The bearing specifications are given in table I.

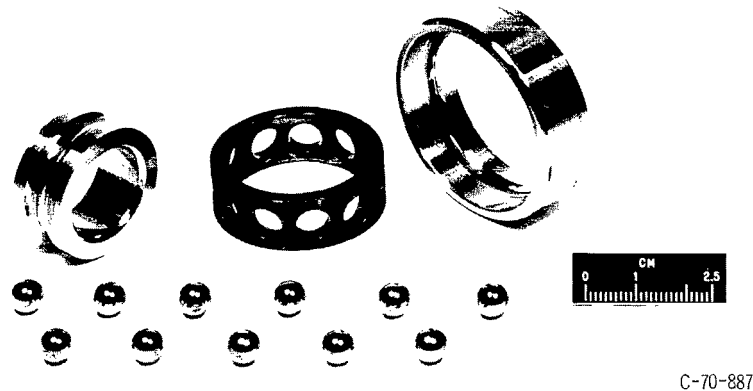


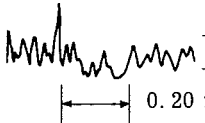
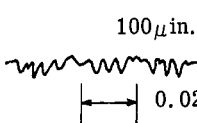

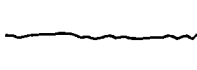

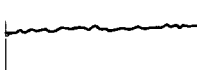
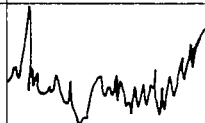
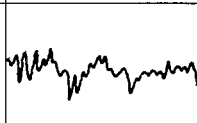
Figure 2. - Typical test bearing (see bearing specifications in table I).

TABLE I. - BEARING SPECIFICATIONS

Type . . . . .	Angular contact outer race relieved
Size . . . . .	20-mm-bore
Material . . . . .	AISI 440 C stainless steel
Number of balls . . . . .	11
Ball diameter, in.(cm) . . . . .	0.281 (0.714)
Curvature for inner and outer race . . . . .	0.52
Radial clearance . . . . .	0.0023 (0.0058)
Ball pocket diametral clearance, in.(cm) . . . . .	0.007 (0.018)
Retainer diametral clearance, in.(cm) . . . . .	0.011 (0.028)



TABLE II. - COMPOSITION AND PHYSICAL PROPERTIES OF RETAINER SUBSTRATE

Bearing	Retainer material	Retainer hardness, Rockwell A	Retainer inside-diameter profile	
			In circumferential direction	In axial direction
4-CB	Cast bronze, percent	24	 $100 \mu\text{in. (} 2.54 \mu\text{m)}$ $0.20 \text{ in (} 0.51 \text{ cm)}$	 $100 \mu\text{in. (} 2.54 \mu\text{m)}$ $0.020 \text{ in. (} 0.051 \text{ cm)}$
10-CB	Cu . . . . . 88			
	Sn . . . . . 11			
	Impurity . . . . . 1			
1-SS	Stainless steel AISI 440 C	61		
5-SS				
2-Cu	Copper OFHC, percent	35		
3-Cu	Cu . . . . . 99.8			
4-Cu	Impurity . . . . . 0.2			
2-SM	AMS 4892 (S-monel), percent	42		
3-SM	Ni . . . . . 63			
4-SM	Cu . . . . . 30			
	Si . . . . . 4			
	Fe, Mn . . . . 3			
1-PB	Porous bronze, percent	$6R_F$		
3-PB	Cu . . . . . 90			
	Sn . . . . . 10			

## Test-Bearing Retainers

Five different substrate materials were investigated for use as bearing retainers. All retainers evaluated were one-piece machined construction and were inner-race located. See table II for material composition and specifications.

## PROCEDURE

### Cleaning Procedure

The balls, races, and retainers were cleaned in an ultrasonic cleaner using a trichloroethane solvent. They were stored in a vacuum desiccator for at least 2 hours before being weighed. Profile traces were made across the inner-race groove. In addition, profiles were taken circumferentially and axially along the inside diameter of the retainer. After tracing, the bearing components were recleaned in three solvents (trichloroethane, acetone, and alcohol) before burnishing.

### Burnishing Procedure

Dry molybdenum disulfide ( $\text{MoS}_2$ ) powder was used to burnish the bearings. The  $\text{MoS}_2$  particle size ranged from 5 to 40 micrometers. The burnishing was accomplished in two steps. First,  $\text{MoS}_2$  was worked into the race grooves with a wire brush. A back and forth brushing motion in the direction of ball motion was used for about 10 minutes. Second, the bearing was reassembled and placed on the burnishing motor shaft. The burnishing fixture consisted of a 1/4-horsepower (186-W), 115-volt ac motor operating at 1725 rpm in a vertical position. A 5-pound (22 N) weight counterbored to receive the bearing outside diameter was applied during burnishing.

The  $\text{MoS}_2$  was dispersed into the rotating bearing from a plastic squeeze bottle as an air-powder mist. This was done about every 10 minutes for approximately 3 hours. The bearing was then removed from the burnishing motor shaft and shaken lightly to remove excessive  $\text{MoS}_2$  powder.

The burnishing was accomplished in an air conditioned room. The temperature was set at 70° to 72° F (294 to 295 K); the humidity was not controlled.

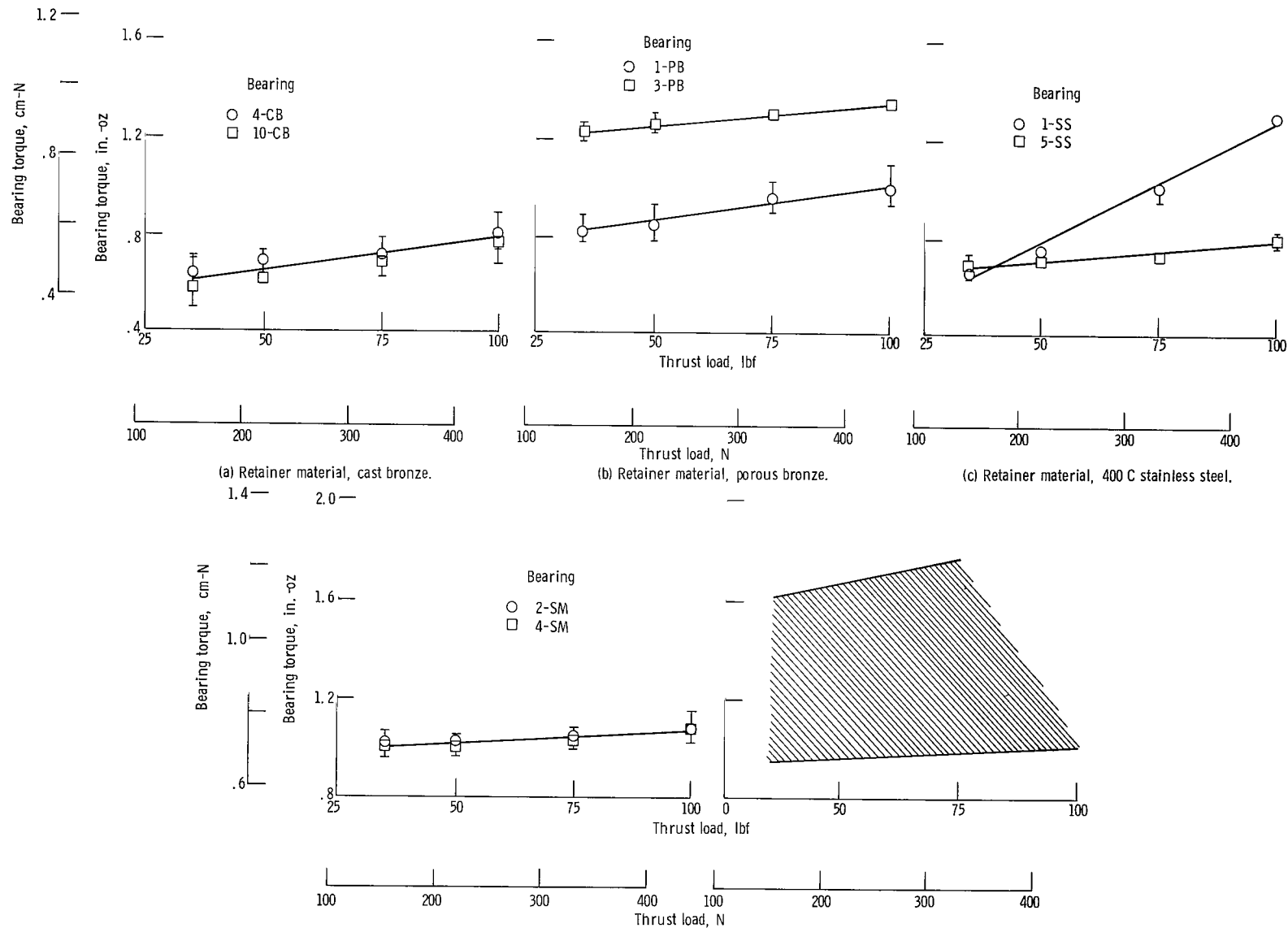


Figure 3. - Bearing torque as function of thrust load. Bearing speed, 3600 rpm; vacuum pressure,  $10^{-10}$  torr ( $1.3 \times 10^{-8}$  N/m<sup>2</sup>).

## Test Procedure

The test bearing was installed, and the test chamber was pumped down to the operating pressure of approximately  $10^{-10}$  torr ( $1.3 \times 10^{-8}$  N/m<sup>2</sup>). The initial static torque with respect to zero beam deflection was recorded. The drive motor was started, and the test bearing was accelerated to the running speed of 3600 rpm. The bearing was operated at an initial thrust load of 35 pounds (156 N). The bearing was subsequently run at 50-, 75-, and 100-pound (222-, 334-, 445-N) thrust load. The torque values were recorded continuously at each load condition. Normally, a test run for a particular bearing consisted of an increasing followed by a decreasing step load sequence, with a 20-minute run time at each load condition. Test runs for most bearings were repeated several times to determine the effect of run time on bearing torque and whether the torque value was repeatable at the same load.

## Torque Data Reduction

Bearing torque was recorded continuously at each load condition for a period of about 20 minutes. This procedure was repeated several times, when possible, with each bearing and each load condition. The bearing torque that is plotted in figure 3 is the arithmetic mean value or average for all test runs at a given load. The range indicated for each data point was determined by the lowest and highest average torque value of the several repeat runs. The average torque value for each run is obtained in the following way: (1) a torque value  $\tau_i$  is estimated for each half-minute interval; (2) then all  $\tau_i$  were averaged over the run period for a given load.

## RESULTS AND DISCUSSION

### Bearing Torque and Thrust Load

Figure 3 illustrates the effect of bearing thrust load on the average bearing torque for the five different retainer materials. The bearings were run at 3600 rpm in a vacuum of  $10^{-10}$  torr ( $1.3 \times 10^{-8}$  N/m<sup>2</sup>). The ambient bearing outer-race temperature normally ranged between 65° and 110° F (291 and 316 K). Bearing torque for all load conditions was approximately of 1 inch-ounce (0.7 cm-N). The bearing friction coefficient for this torque at a 100-pound (445-N) thrust load is 0.0016 when referred to the bearing bore. This compares with a typical friction coefficient of 0.0013 for a conventional oil lubricated bearing.

Bearing torque increased linearly with increasing thrust load for each bearing. Considering combined bearing results for each retainer substrate material, the bearings using cast bronze retainers were consistently lower in bearing torque. The bearings with OFHC (oxygen-free high conductivity) copper retainers exhibited poor repeatability of bearing torque for each load condition.

Johnston and Moore (ref. 9) have shown the effects of burnishing  $\text{MoS}_2$  on the copper surfaces under controlled conditions of surface finish of substrate, load, and relative humidity of the surrounding atmosphere. They indicate that for a given number of traverses of the burnisher, the surface density of deposited  $\text{MoS}_2$  increases with increasing surface roughness. They reason, "It follows, therefore, that rougher surfaces have a larger reserve of lubricant and films formed on them would be more resistant to the attrition caused by continued sliding. However, very rough surfaces would have localized contact areas and the resultant high pressures would be liable to initiate seizure and wear." Referring to table II, the surface roughness on the inside diameter of the copper substrate was quite similar to that of the stainless steel in both the circumferential and axial directions. The torque reproducibility for an individual bearing using a stainless-steel retainer was good (fig. 3(c)). In view of this, surface roughness does not appear to be responsible for the erratic torque measured when using the copper retainers.

Johnston (ref. 9) indicates that humidity during the burnishing procedure is highly influential on film formation. According to Johnston, a greater number of burnishing strokes under dry conditions (7 percent relative humidity) is required to obtain the same surface density of  $\text{MoS}_2$  as obtained at high relative humidity (~86 percent). The humidity conditions during burnishing were not controlled in this experiment. However, it is believed that a burnishing time of 3 hours was more than sufficient to establish an adequate film at even the driest conditions (5 to 10 percent relative humidity).

Lancaster (ref. 10) indicates that substrate hardness affects the performance of  $\text{MoS}_2$  as a solid lubricant. However, table II shows that the hardness of the copper substrate is within the range of the hardness of the cast bronze and the nickel base alloy (AMS 4892). Results of this investigation indicated these two materials worked well with  $\text{MoS}_2$ . It is therefore unlikely that the hardness of the copper was responsible for the poor performance.

Przybyszewski and Spalvins (ref. 11) measured friction of OFHC copper riders sliding on  $\text{MoS}_2$  sputtered OFHC copper disks. They obtained high and erratic friction coefficients with this combination. They concluded (1) that continuous films of  $\text{MoS}_2$  are extremely difficult to obtain on OFHC copper surfaces and (2) that a sputtered film of  $\text{MoS}_2$  on copper does not function successfully as a lubricant because of its extremely poor adherence to this metal. It is established that poor film adherence of  $\text{MoS}_2$  to

OFHC copper was probably responsible for the erratic friction torque measured with these bearings.

The retainer material used for bearings 1-PB and 3-PB was porous bronze. Retainer 3-PB was heated in a hydrogen furnace to 1400<sup>0</sup> F (1033 K) in addition to the usual preparation. This was done to remove all traces of oil within the porous material that might not have been flushed out during the cleaning procedure. The bearing torque of bearing 3-PB was approximately 50 percent higher than that of 1-PB (fig. 3(b)). The traces of residual oil within the pores of retainer 1-PB was apparently beneficial to the bearing torque.

## Bearing Torque and Run Time

Each bearing was run several times at thrust loads from 35 to 100 pounds (156 to 445 N). Figure 4 is a plot of the average torque against the median time at 50- and 100-pound (222- and 445-N) thrust loads for the five retainer materials. The figure indicates that bearing torque generally increased with increasing run time after 200 minutes. This seems to indicate a deterioration of the burnished MoS<sub>2</sub> film. The wearing through or deterioration of the MoS<sub>2</sub> lubricating film using a copper retainer is extremely rapid (fig. 4(e)) in comparison with that of the other retainer substrates. The test of bearing 2-Cu was terminated at 75-pound (334-N) thrust load because of a sharp increase in torque. This torque increase was sufficient to cause disengagement of the wire connecting the transducer beam with the bearing housing. The total run time of this bearing (406 min) was considerably more than for bearing 3-Cu, which was terminated in the same manner after only 236 minutes. From these results, it is apparent that the burnished MoS<sub>2</sub> did not form an adequate lubricating film with sufficient endurance on the copper substrate.

Run time has a small effect on bearing torque. The effect is about the same at a 50-pound (222-N) thrust load as it is at a 100-pound (445-N) thrust load; that is, bearing torque generally increases linearly with run time and with about the same slope. Within the load range investigated, the film does not wear through more noticeably for the higher thrust loads as might be expected.

## Post-Run Inspection

There was no extensive wear of the bearing components as indicated by weight measurements or surface profile traces of the inner-race grooves. The post-run condition of each bearing is given in table III. The bearings using copper retainers were in

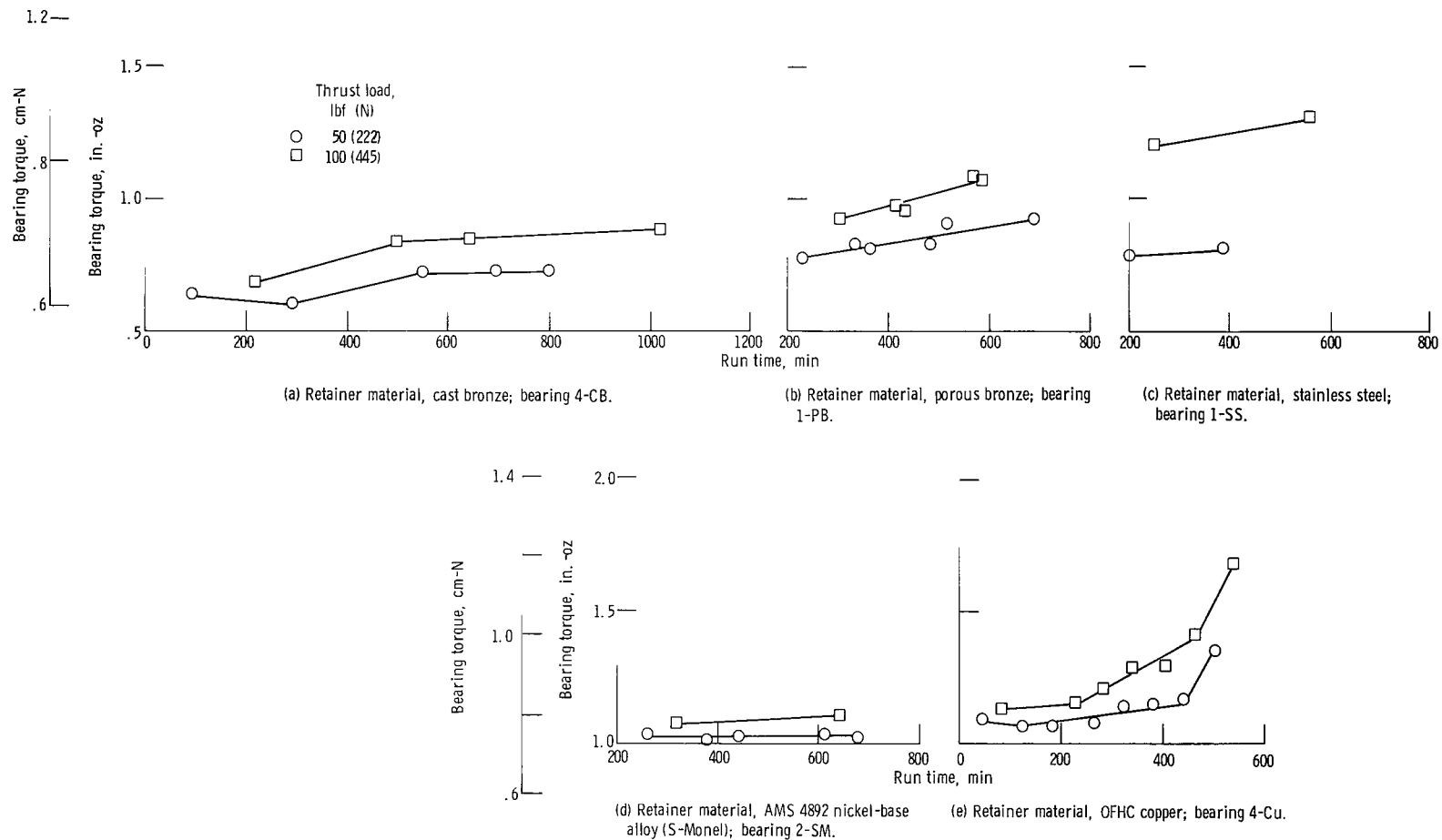


Figure 4. - Bearing torque as function of run time. Bearing speed, 3600 rpm; vacuum pressure,  $10^{-10}$  torr ( $1.3 \times 10^{-8}$  N/m<sup>2</sup>).

TABLE III. - SUMMARY OF BEARING TEST RESULTS

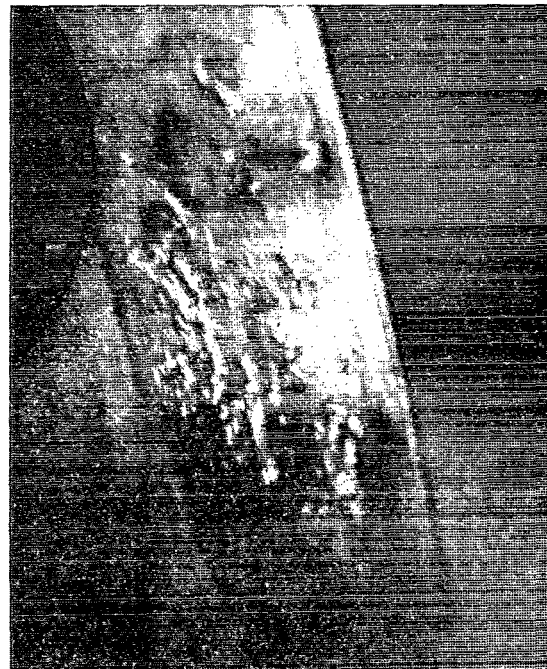
[Load, 35 to 100 lbf (155.4 to 440 N); speed, 3600 rpm; pressure,  $10^{-10}$  to  $10^{-11}$  torr ( $1.33 \times 10^{-8}$  to  $1.33 \times 10^{-9}$  N/m<sup>2</sup>)]

Bearing	Run time, min	Bearing torque		Post Run condition			
		in.-oz	cm-N	Outer race	Inner race	Ball set	Retainer
4-CB	1234	0.58 to 0.90	0.41 to 0.63	Bronze transfer to ball path	Bronze transfer; purple coloration in ball path region	Shiny ball set; ball path marks visible	Nonuniform coating of MoS <sub>2</sub> on one side of inner land
10-CB	352	0.50 to 0.81	0.35 to 0.57	Glazed uniform MoS <sub>2</sub> coating; some pits filled with MoS <sub>2</sub>	Glazed MoS <sub>2</sub> coating along ball path; pits filled with MoS <sub>2</sub>	Very good condition no metal transfer	Nonuniform MoS <sub>2</sub> coating on i.d. of retainer
1-SS	726	0.62 to 1.32	0.44 to 0.93	Good condition	Good condition; rubbing marks on thrust shoulder land	Shiny; ball path evident	Even wear on i.d.
5-SS	415	0.62 to 0.81	0.44 to 0.57	Glazed coating along ball path; adhesive wear	Glazed coating; scratch marks at low contact angles; scuffing or adhesion marks at high contact angle	Glazed surface; patches of MoS <sub>2</sub>	Regions of MoS <sub>2</sub> with numerous blister like scales of MoS <sub>2</sub>
2-Cu	406	0.97 to 1.78	0.68 to 1.26	Scuffing and scratching along ball path	Scuffing and scratching along ball path	Small crack on one ball; shiny and dark	Uniform wear on i.d.; rubbing on o.d.
3-Cu	236	-----	-----	Glazed coating; copper particle flash; scratch marks	Glazed coating; two copper particle flashes; copper colored rubbing marks on shoulders	Scuffing and copper particle flash marks surrounded by heat marks	Uniform coating on i.d.; deformation in ball pockets
4-Cu	551	1.04 to 1.68	0.73 to 1.18	Glazed MoS <sub>2</sub> coating in track; light but long scratch on outer edge of ball track	Heat mark along path semicircumference; glazed coating; good condition	Light copper color transferred; numerous fine scratch marks; some heat marks	Abundance of MoS <sub>2</sub> blisters on land; some are broken exposing copper; considerable MoS <sub>2</sub> film on land surface
2-SM	712	1.00 to 1.12	0.71 to 0.79	Good condition	Good conditions except for pit on wear track	Very good condition	Good condition
3-SM	210	-----	-----	Glazed coating; small pit observed; skid mark and scratch	Glazed coating; scratch marks	Good condition; ball path evident	Uniform rubbing on i.d.; good condition
4-SM	623	0.97 to 1.16	0.68 to 0.82	Glazed ball groove; MoS <sub>2</sub> patches	Glazed ball groove; MoS <sub>2</sub> blisters noted on semicontinuous film on land	No evidence of scratching; shiny and glazed; MoS <sub>2</sub> patches	Scattered but dense deposits of MoS <sub>2</sub> on land blisters noted within these deposits.
1-PB	1044	0.77 to 1.09	0.54 to 0.76	Some scuffing	Some scuffing; bronze transfer	Dark and shiny orange peel appearance	Uneven wear; nonuniform film on retainer i.d.
3-PB	283	1.18 to 1.34	0.83 to 0.95	Glazed coating; occasional scratches outside ball path	Glazed coating; good condition; no scratches noted	Glazed coating; patches of MoS <sub>2</sub>	Highly glazed MoS <sub>2</sub> in rubbing and sliding areas; uniform rubbing on i.d.

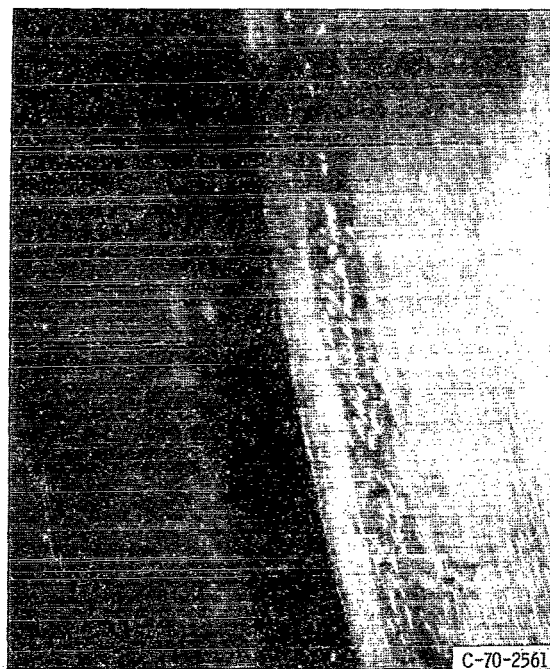




(a) Blister formation on inner-race land of retainer 4-Cu. Retainer material, copper.



(b) Blister formation on inner-race land retainer 4-SM. Retainer material, AMS 4892 nickel-base alloy (S-Monel).



(c) Blister formation on inner-race land of bearing 4-SM.

Figure 5. - Molybdenum disulfide film blisters. X15.

the poorest condition as indicated by the scuffing and scratch marks in the race grooves. There was evidence that small pieces of copper had broken from the retainer substrate and had been rolled or pressed into the race grooves and balls during the run. This is described in table III as copper particle flash marks. Some of these marks were accompanied by bluish coloration of the stainless steel surrounding the copper particle. These bluish colored marks have the appearance of stainless steel that has been oxidized at a high temperature.

The other bearings were generally in much better condition as indicated by the relatively fewer scuff marks in the race grooves and ball sets. There was evidence of film repair with bearing 10-CB. The inner and outer races of this bearing had pits filled in with  $\text{MoS}_2$ . It is believed these pits were formed by adhesive wear and were filled in with excess loosened  $\text{MoS}_2$  powder by the action of the balls. All bearings except those having copper retainers were in good running condition.

Especially noticeable were the blister formations of  $\text{MoS}_2$  on the inner land of the retainer 4-Cu. These blisters are illustrated in figure 5(a). Blister like formations were also noticed on the inner land of retainers 4-SM (fig. 5(b)) and 5-SS, but to a lesser extent. A very small amount of blistering was noted on the retainer locating surface of the inner race of bearing 4-SM (fig. 5(c)). The  $\text{MoS}_2$  film acquires a metallic lustre in the region of blister formation. According to Salomon (ref. 12), this metallic lustre promotes the blister formation. The blister formation is brought about more rapidly in the presence of oxygen, and under conditions of low relative humidity (i.e., less than 7 percent). To our knowledge, the effect that substrate material has in the formation of blisters is unknown. It would have been of interest to determine whether blister formation and subsequent blister breakup was responsible for the high friction torque measured for bearings using copper retainers.

## SUMMARY OF RESULTS

Twenty-millimeter-bore ball bearings with metallic retainers were burnished with molybdenum disulfide and run at pressures of  $10^{-10}$  torr ( $1.3 \times 10^{-8}$  N/m<sup>2</sup>). The burnished surfaces were the race grooves, inner-race-riding land, ball set, retainer land, and retainer ball pockets. Retainers were fabricated of five different alloys which served as the substrate material for the  $\text{MoS}_2$  coating. The five alloys consisted of cast bronze, porous bronze, oxygen-free high-conductivity copper, AISI 440 C stainless steel, and AMS 4892 nickel-base alloy. The lubricating technique and the retainer materials were evaluated by measurement of bearing friction torque in the vacuum environment. The bearings were operated at 3600 rpm, at thrust loads from 35 to 100 pounds (156 to 445 N) for run times as long as 20 hours.

The investigation produced the following results:

1. Low-bearing-friction torque in ultrahigh vacuum was obtained with bearings burnished with molybdenum disulfide. The magnitude of the bearing torque was comparable to that of conventional oil-lubricated bearings.

2. The bearings using cast-bronze retainers were consistently lower in bearing torque than bearings using porous bronze, AISI 440 C stainless steel, and AMS 4892 retainers. Oxygen-free high-conductivity copper exhibited the highest and most erratic bearing torque. In addition, the reproducibility for oxygen-free high-conductivity copper was poor, which resulted in a wide range of values of bearing torque for the load range investigated.

3. An increase in bearing torque was noted with increasing run time for most bearings. This increase with run time was not significantly different for different loads in the load range investigated.

4. The bearings with cast bronze, porous bronze, AISI 440 C stainless steel, and AMS 4892 retainers were in good running condition for run times as long as 20 hours. Some bearings exhibited blisters of molybdenum disulfide which was believed to be potentially detrimental to smooth bearing performance.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, August 6, 1970,  
129-03.

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